

Cloning and characterization of human chemokine receptors

Christine A. Power and Timothy N. C. Wells

Chemokines are a superfamily of proteins that have molecular masses of between 8 and 10 kDa and that display amino acid sequence identities of between 20 and 90%. They play a number of roles in inflammatory processes, including the selective recruitment and activation of leukocytes¹. Their amino acid sequences contain four distinctive, conserved cysteine residues (Fig. 1). CXC (or α) chemokines, in which the first two cysteines are separated by one amino acid, are generally involved in neutrophil recruitment and activation and are implicated in acute inflammatory diseases. CC (or β) chemokines, in which the first two cysteines are adjacent, exert their

effects on other leukocyte populations such as monocytes, T cells, eosinophils and basophils, and are implicated in chronic inflammatory conditions². Lymphotactin³ is a recently described protein that contains only two of the four conserved cysteine residues but otherwise retains overall sequence homology to other members of the chemokine family; this protein is probably the prototype of a third class of chemokines referred to as C chemokines.

The specific effects of chemokines on inflammatory cells are mediated by a family of G protein-coupled, seven transmembrane (7TM) receptors. Despite the fact that at least 21

human chemokines have been identified to date, only seven human chemokine receptors have been cloned. Two virally encoded chemokine receptors and the more distantly related erythrocyte Duffy antigen receptor (DARC), which also binds chemokines, have also been identified (Fig. 2). The ligand specificities and cellular distribution of these receptors are shown in Table 1.

CXC chemokine receptors

Two receptors for the CXC chemokine interleukin 8 (IL-8) have been identified. The IL-8 receptor A (IL8_A) was identified by expression cloning using 125 I-labelled IL-8 (Ref. 4). The IL-8 receptor B (IL8_B) was identified in a dibutyryl cAMP-stimulated HL-60 cell DNA library by screening with a rabbit N-formyl-methionyl-leucyl-phenylalanine (fMLP)-like receptor DNA probe⁵. Both IL8_A and IL8_B are predominantly expressed in polymorpho-

CXC chemokines

IL-8	SAKELRCQCICKTYSKPFHPKFIKERVIESGPHCANTEIIVKLS.DRELCLDPKENWVQRVVEKFLKRAENS
NAP-2	AELRCMCIKTTSG.IHPKNIQSLEVIGKGTHCNQVEVIATLKD.GRKICLDPDAPIKKIVQKKLAGDESAD
ENA-78	AGPAAAVLRELRCVCLQTTQG.VHPKMISNLQVFAIGPQCSKVEVVASLKN.GKEICLDPPEAPPLKKVIQKILDGGNKEN
GRO α	ASVATELRCQCQLTQG.IHPKNIQSUVNPKSPGPCHCAQTEVIATLKN.GRKACLNPAPIVKKIEKMLNSDKSN
GRO β	APLATELRCQCQLTQG.IHLKNIQSUVKVKSPGPCHCAQTEVIATLKN.GQKACLNPAPIVKKIEKMLKNGKSN
GRO γ	ASVUTELRCQCQLTQG.IHLKNIQSUVNVRSPGPCHCAQTEVIATLKN.GKKACLNPAPIVKKIEKILNKGSTN
IP-10	VPLSRTVRCCTCISISNQPVNPRSLKEIIPASQFCPRVEIIATMKKKGZKRCRCLNPESKAICNLKAVSKEMSKRSP
GCP-2	GPVSAVLTELRCRCTLRTVTLR.VNPKTIGKLQVFAGPQCSKVEVVASLKN.GKQVCLDPPEAPFLKKVIQKILDGNGNK
SDF-1	GKPVSLSYRCPCRFFESH.VARANVKHLKILN.TPNCALQIVARLNKNN.RQVCIDPKLKWIQEYLEKALNK
PF4	EAEEEDGDLQCLCVKTTSQ.VRPRHITSLEVIAKAGPHCPTAQLIATLKN.GRKICLQLQAPLYKKIEKKLLES
MIG	TPVVRKGRCSCISTNQGTIHLQLSLXDLKQFAPSPSCEKIEIIATLKN.GVQTCLNPDSADVKELEKKWEKQVSQ

CC chemokines

RANTES	SPYSSDT.TPC.CFAYIARPLPRAHIKEYFYTSGK..CSNPAAVVFVTRKN.RQVCANPEKKWVREYINSLEMS
I309	SKSMQVPFSRC.CFSFAEQEIPLRAILCYRNTSSI..CSNEGLIFKLRKG.KEACALDTVGVWVQRHRIKMLRHCPSKRK
MIP-1 α	ASLAADPTPAC.CFSYTSRQIIPQNFIAFYFETSSQ..CSKPGVIFLTKRS.RQVCADPSEEWVQKVYSDLELSA
HCC1	TKTESSSRGPYHPSEC.CFTYTTYKIPRQRIMDYYETNSQ..CSKPGIVFITKRG.HSVCTNPSDGWVQDYIKDMKEN
MIP-1 β	APMGSDPPTAC.CFSYTAARKLPRNFVVDYYETSSL..CSQPAVVFQTKRS.KQVCADPSESWVQEVYVDLELN
MCP-1	QPDAINAPVTC.CYNFTNRKISVQRLASYRITSSK.CPKEAIVFKTIVA.KEICADPKQKVVQDSMDHLQQTQTPKT
Eotaxin	GPA..SVPTTC.CFNLANRKIPLQRLSYRITSGK..CPQKAVIFKTKLA.KDICADPKKKVVQDSMKYLDQKSPTPKP
MCP-2	QPDVSISIPTC.CFNVINRKIPIQRLSYRITNIQ.CPKEAIVFKTKRG.KEVCADPKERKVRDMSMKHLQIFQNLKP
MCP-3	QPGVINTSTTC.CYRFINKKIPKQRLESYRRTTSSH.CPREAVIFKTKLD.KEICADPTQKVVQDFMKHLDDKKTQTPKL

C chemokine

Lymphotactin	GVEVSDKRT.CVSLTMQRLPVSRKTYTITEG...SLR.AVIFITKRGK..VCADPQATWVROVVRSMRDKSNTRNNMQT.
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Fig. 1. Amino acid sequence alignment of human chemokines. Chemokines have been grouped as CXC, CC or C chemokines, with the conserved cysteine residues in red. ENA-78, epithelial-derived neutrophil attractant-78; IP-10, interferon γ inducible protein 10; GCP-2, granulocyte chemotactic protein 2; SDF-1, stromal cell derived factor 1; PF4, platelet factor 4; MIG, monokine induced by interferon γ .

C. A. Power,
Research Scientist,
and
T. N. C. Wells,
Head of Protein
Biochemistry,
Grazo Institute for
Molecular Biology,
1228 Plan-les-Ouates,
Geneva, Switzerland.

C U R R E N T A W A R E N E S S

IL8 _A	.....MSNITDPQ MWDFDDLN...FTGMPPAD EDYSPCMLET E....TLNK YVIIAYALV FLLSLLGNSL VMLVILY..S RVGRSVTDVY	100
IL8 _B	.....MESDSFED FWKGEDLSNY SYSSTLPPFL LDAAPCEPES L....EINK YFVVIYALV FLLSLLGNSL VMLVILY..S RVGRSVTDVY	
CC CK _{2B}	....MLSTSR SRFIRNTNES GEEVTTFFDY DY..GAPCHK FD.....V K....QIGA QLPPPLSIV FIFGFCVGNML VVJLIL..C KKLKCLTDVY	
CC CK ₅	.....MD YQVSSPIYDI NYTSEPCQK IN.....V K....QIAA RLLPPLSIV FIFGFCVGNML VVJLIL..C KRLKNSMFTDIY	
CC CK ₁	.....MTP..NT TEDYDMMTEF DYGAATPCQK VN.....E R....AFGA QLPPPLSIV FVIGLVGNIL VVJLVLQ..Y KRLKNSMFTDIY	
CC CK ₃	.....MTTSLDT VETFGTTSYD D.VGVLCEK AD.....T R....ALMA QFVPPPLSIV FTVGLLGNV VVMIK..Y RRLRIMTNIY	
CC CK ₄	.....MN PTDIADTLD ESIYSVYLY E.SIPKPCTK EG.....I K....AFGE LFLPPLSIV FVFGLLGNV VVJLVLQ..Y KRLRSMFTDVY	
HCMV US28	.....MPTPTTTA ELTTEPFDYDE DATPCVFTDV L....NQSK PVTPLPVGVV FFLFGSIGNFL VIFTITW..R RRIQCSGDVY	
HSV ECRF3	.....MEVKL DFSSSEDFSNY SYNGSDIYV GDVAPCVNNF L....ISE SALAFIYVLM FLCNAIGNSL VLRFLK..Y RAQAQSFDFY	
DARC	MASSGYVILQA ELSPTENSS QLDfedWNS SYGVNDSFPD GDYDANLEAA APCHSCNLLD DSALPFFILT SVLGILASST VLFMLFRPLF RWQLCPGWPV	
		101
IL8 _A	LLNLALADLL FALTLPIWAA .SKVNGWIFG TFLCKVVSLL KEVNFGYSGIL LLACISVDRY LAIVHATRNL TQKRH.LVKF VCLGCWGLSM NLSLPPPLFR	
IL8 _B	LLNLALADLL FALTLPIWAA .SKVNGWIFG TFLCKVVSLL KEVNFGYSGIL LLACISVDRY LAIVHATRNL TQKRH.LVKF ICLSIWCLSL LLALPVLLR	
CC CK _{2B}	LLNLAISSL FLITLPLWAH SA.ANEVWFG NAMCKLPTGL YHIGYFGGIF FIILLTIDRY LAIVHAVFAL KARTVTEGVV TSVITWLVAW FASVPGIIFT	
CC CK ₅	LLNLAISSL FLITLPLWAH YA.AAQWDFG NIMCQLLTGL YFIGFFSGIF FIILLTIDRY LAIVHAVFAL KARTVTEGVV TSVITWWVV FASLPGIIFT	
CC CK ₁	LLNLAISSL FLITLPLFWID YKLKDDVVFG DAMCKILSGF YYTGLYSEIF FIILLTIDRY LAIVHAVFAL RARCVTEGVV TSIVIWLALI LASMPLGYES	
CC CK ₃	LLNLAISSL FLVTLPLFWIH YVRGHNNVFG HGMQNLLSGF YHTGLYSEIF FIILLTIDRY LAIVHAVFAL RARCVTEGVV TSIVIWLGLAV LAALPEFIFY	
CC CK ₄	LLNLAISSL FVFLSPFWGY YA.ADQWVFG LGLCKMISWM YLVCYSGIF FVYLMNSDRY LAIVHAVFSL RARTLTYGVI TSLATWSAV FASLPGFLES	
HCMV US28	FINLAAADLL FVCTLPLWQ YLLJHNS.LA SVPCTLLTAC FYVAMFASLC FITEIALORY YATVY...N RYRPVKQACL FEIFKWIYAV IIIAIPHFMVV	
HSV ECRF3	MMGFCLNSLF LAGYLLMRL..LRMPEIPMN TELCKLEAFF LNLSTIYWSF IIUPISVLRG LLIFCATRML VKTFLIGQVF LC.CSFVLAQ PGALPHMVNT	
DARC	LAQLAVGSAL FSIVVPPVLAQ.....GLG STRSSALCSL GYCIVWYGSF AQALL.LGCH ASLGHRLGAG QVPGLTGLT VGI..WGVA LLTLPVTLAS	
		201
IL8 _A	QAYHPNNSSP UCYEVLGNDT AKWFMVLRIL PHTFGFIVPL FVMLFCYGF LRTLFKAHMG QK.HRAMRV T FAVVLIFLLC WLWPNLVLLLA DTLNRT.QVI	
IL8 _B	RTVYSSNVSP ACYEDMGNNT ANWRLMILLRIL PQSPGFIVPL LIMLFCYGF LRTLFKAHMG QK.HRAMRV T FAVVLIFLLC WLWPNLVLLLA DTLNRT.QVI	
CC CK _{2B}	KCQKEDSVVY CGPYFFPRG..WNNFHTIM RNILGLVLP LIMVICYSGI LKTLRRCRNE KKRHRRAVRV T FTMIVYFLF WTPYNIVILL NTFQEF.FGL	
CC CK ₅	KSQKEGLHYT CSSHPYPSQY QFWKMFQTLK IIVLGLVLP LVMVICYSGI LKTLRRCRNE KKRHRRAVRV T FTMIVYFLF WAPYNIVILL NTFQEF.FGL	
CC CK ₁	KTQWEEFTHMT CSLHPPHESL REWXLFLQALK LNLFLGVLPL LVMICYTG I IKILLRRPNE KK.SKAVRLI FVIMIIFFLF WTPYNLTILY SVFQDF.LFT	
CC CK ₃	ETEELFEETL CSALVPEDTV YSMRHFHTLR MTIFCLVLP LVMICYTG I KTLRRCPSK KK.YKAIRL FVTMAVFFF WTPYNVAILL SSYQSI.LFG	
CC CK ₄	TCYTERNHTY CKTKYSLNST.TWKVLSSLE INILGLVPL GIMLFCYSMI IRTLQHCKNE KK.NKAVKMI FAVVVLFLCF WTPYNIVLPL ETLVEL.EVL	
HCMV US28	T..KXDNQCM TDYDYLEVS..YPIIILNVE LMLGAFVIPL SVISYCYYRI SRIVAVSQSR HK.GRIVRVL IAVVVLVII F WLPYHLLTFV DTLKLL.KWI	
HSV ECRF3	SYYEPSSCIE EDGVLTQQLR TKLNCFHTW...YSFAGPL FITVICYSMS CYKLFKCKLS.KRAEWVII TMTLIPFIVF CIPYYIMESI DTLRV.GVI	
DARC	GASGGLCTLI YSTEKA...LQATHT VACLAIFVLL PLGLGAKGL KKALGMGPW W.....MNILWAWFIP WWPNGVVLG DFLVRSKLLL	
		301
IL8 _A	QETCERRNNI GRALDATEIL GFLHSCLNPI IYAFIGQNFR HGFLKILAMH GLVSKEFLAP HRVTSY.TSS SVNVSSNL	388
IL8 _B	QETCERRNNI GRALDATEIL GILHSCLNPL IYAFIUCQKFR HGLLKILAMH GLISKDSLKP DSRPSFGSS SGHTSTTL	
CC CK _{2B}	SN.CESTSQL DQATQVTEL GMTHCCINPI IYAFVGEKFR RYLSVFFPK. HITKRFCKQC PVYFRETVDG VTSTATPSTG EQEISAGL	
CC CK ₅	NN.CSSSNRL DQAMQVTEL GMTHCCINPI IYAFVGEKFR NYLLVFFQK. HIAKRFCKCC STFQQEAPER ASSVYTRSTG EQEISVGL	
CC CK ₁	HE.CEQRSHL DLAVQVTEVI AYTHCCVNF IYAFVGERFR KYLRLQFLHR. RVAVHLLVKNL PFLSVDRLER VSST.SPSTG EHELSAGF	
CC CK ₃	ND.CERSKHL DLVMLVTEVI AYSHCCMNFV IYAFVGERFR KYLRLHFFHR. HLLMLHGRYI PFLPSEKLER TSSV.SPSTA EPELSIVF	
CC CK ₄	QD.CTFERYL DYAIQATEL AFVHCCCLAPI IYFFLGEKFR KYIQLQFKTC RGLGVLQYQC GLLQIYSAUT PSSSYTQSTM DHDLHDAL	
HCMV US28	SSSCPEPERSL KRALILTESL AFCHCCCLAPI LYFVWGTFR KNYTVCWPSF ASDSP?PAMYP GTTA.....	
HSV ECRF3	EETCAKRSIA VYGIQCTYML LVLYYCMLFL MFAMPGSLPK QRMAAWCKTI CHC.....	
DARC	LSTCLACQQL DLLLNLAEL AILHCVATPL LLALFCHQAT RTLLPSLPLP EGKSSHLDL GSKS.....	

Fig. 2 Amino acid sequence alignment of chemokine receptors. Highly conserved residues are in red. Database accession codes for the sequences used in this alignment are M68932 for IL8_A, M73969 for IL8_B, L10918 for CC CK₁, U03982 for CC CK_{2B}, U28694 for CC CK₃, X85740 for CC CK₄, X91492 for CC CK₅, U01839 for DARC, X17403 for HCMV US28, S76368 for HSV ECRF3. To facilitate the alignment, CC CK_{2A} has not been included.

nuclear leukocytes and bind IL-8 at high affinity; however, the IL8_A receptor is specific for IL-8, whereas IL8_B can also bind other CXC chemokines at high affinity, such as neutrophil-activating peptide 2

(NAP-2) and growth related gene product α (GRO α) or melanoma growth stimulating activity (MGSA) [and probably other chemokines containing a Glu-Leu-Arg (ELR in Fig. 1) sequence motif preceding the con-

served CXC motif]. Neither of these receptors can bind CC chemokines.

CC chemokine receptors

Degenerate oligonucleotide PCR primers, based on the conserved

Table 1. The chemokine receptor family: summary of ligand-binding specificities and cellular distribution of human chemokine receptors

Receptor	Ligand (K_d) ^a	mRNA expression	Murine homologue	Refs
IL8 _A	IL-8 (1.7 nM)	M, N, T	—	43
IL8 _B	IL-8 (0.8 nM), GRO α (1.2 nM), NAP-2	B, Bp, E, M, N, T,	mlL8	42, 43
CC CK ₁	MIP-1 α (10 nM), RANTES (0.6 nM), MCP-3 (0.7 nM)	B, E, M, M Φ , N, T,	mMIP1 α	6, 8, 9, 44
CC CK _{2B}	MCP-1 (0.26 nM), MCP-3 (6 nM)	B, Bp, M, T,	mJE-R	11, 12, 45
CC CK ₃	Eotaxin	E, M,	mMIP1 α RL2	44
CC CK ₄	MIP-1 α (14 nM), RANTES (9 nM), MCP-1	B, Bp, M, T,	mCC CK _{4A}	18
CC CK ₅	MIP-1 α , MIP-1 β , RANTES	—	mMIP1 α	45, 46
DARC	IL-8 (20 nM), GRO α (24 nM), RANTES (42 nM), MCP-1 (34 nM)	EC (spleen, lung, brain and kidney)	mDARC	22
HCMV US28	RANTES (3.4 nM), MCP-1 (6.1 nM), MIP-1 α (2.5 nM), MIP-1 β (5.1 nM)	—	—	24
HSV ECRF3	GRO α , NAP-2, IL-8	—	—	—

^aNanomolar dissociation constants (K_d) are for recombinant receptors expressed in mammalian cell lines (where available); otherwise, ligand specificity is based on Ca^{2+} mobilization data obtained from *Xenopus laevis* oocytes.

B, B cell; Bp, basophil; E, eosinophil; EC, endothelial cell; M, monocyte; M Φ , macrophage; N, neutrophil; T, T cell.

sequences found in the IL8 receptors and other chemoattractant peptide receptors (such as those for C5a and fMLP), have been used in orphan receptor cloning strategies to identify CC chemokine receptors. Although such an approach has proved useful in identifying at least five distinct receptors (described below), one of the pitfalls of the method is that it cannot identify receptors that belong to a different class from 7TMs.

The CC CK₁ receptor was originally isolated from U937 or HL-60 cell lines^{6,7} and was shown to be activated by macrophage inflammatory protein 1 α (MIP-1 α) and RANTES (regulated on activation normal T-cell expressed and secreted). Binding data reveal low nanomolar dissociation constants for MIP-1 α (Ref. 6), RANTES (Ref. 8) and monocyte chemoattractant protein 3 (MCP-3; Ref. 9). CC CK₂ was cloned from MonoMac6 cells and exists in two alternatively spliced forms, A and B, that differ in their cytoplasmic C-terminal domains¹⁰. Both forms of CC CK₂ mRNA are highly expressed in peripheral blood monocytes. HEK-293 cells stably expressing the receptor bind MCP-1 and MCP-3 at high affinity but surprisingly are unable to bind the closely related MCP-2 (Refs 11, 12). CC CK₃ has been cloned from

activated peripheral blood mononuclear cells¹³⁻¹⁵. The high level of expression of CC CK₃ mRNA in eosinophils is consistent with the finding that it is a receptor for the eosinophil-specific chemoattractant eotaxin^{15,16}. A fourth receptor, CC CK₄, has been identified in the human, immature, basophilic cell line KU-812 (Ref. 17). The receptor mRNA is highly expressed in T cells and IL-5 primed basophils. MIP-1 α , RANTES and MCP-1 can activate this receptor when expressed in *Xenopus laevis* oocytes¹⁸. Direct binding of RANTES and MIP-1 α has also been observed in HL-60 cells transiently expressing CC CK₄ (Ref. 18). More recently, a fifth CC chemokine receptor, CC CK₅ (or ChemR13), has been described^{13,14,19}. CHO-K1 cells stably expressing CC CK₅ can respond to MIP-1 α > MIP-1 β and RANTES in a microphysiometer¹⁹. Although mRNA for this receptor has been detected in the promyeloblastic cell line KG-1A, no data have yet been published regarding its expression in normal cells.

Promiscuous receptors

DARC is a promiscuous chemokine receptor originally identified in erythrocytes²⁰ but also reported in restricted leukocyte populations

and postcapillary, high-endothelial, venules²¹. It is unique as it binds a number of CXC chemokines (IL-8, MGSA and NAP-2) and CC chemokines (RANTES and MCP-1) at high affinity^{22,23}. Despite the overlapping ligand-binding specificities with CXC and CC chemokine receptors, DARC shows less than 30% amino acid identity to these receptors. No signalling pathways have yet been described for the action of DARC.

Virally encoded receptors

Two virally encoded chemokine receptors have been reported. One, encoded by an open reading frame found in human cytomegalovirus US28 (and thus called HCMV US28), encodes a receptor that binds CC chemokines²⁴. The other is a CXC chemokine receptor encoded by an open reading frame in Herpes saimiri virus ECRF3 (HSV ECRF3)²⁵. While both receptors are capable of signal transduction, their significance *in vivo* is unclear. An antiviral role for chemokines in host defence is implied.

Chemokine-receptor-like orphan receptors

Degenerate, oligonucleotide-based, PCR cloning strategies have also

identified a large number of orphan receptors including G protein-coupled receptor 5 (Ref. 26), chemokine β receptor-like 1 (Ref. 27) [or V28 (Ref. 28)], leukocyte derived 7TM receptor (Ref. 29) and Burkitt lymphoma receptor 1 (Ref. 30), the mRNAs of which are generally highly expressed in leukocyte populations, notably T and B lymphocytes. Despite a high degree of sequence identity (30–50%) to known chemokine receptors, specific ligands for these receptors have yet to be identified. This may be because it is difficult to obtain a high level of expression of these receptors in mammalian cell lines, additional cofactors might be required, or it might be due simply to the fact that the physiological ligands have not yet been cloned. Possible roles of these proteins as viral receptors cannot be excluded yet.

Genomic localization

The genes encoding IL8_A and IL8_B co-localize on human chromosome 2q34–35 (Ref. 31), a region that also contains a pseudogene of IL8_B. The genes for CC chemokine receptors appear to be clustered on chromosome 3, with ccckr1, 2 and 5 found at 3p21 (Refs 7, 19) and ccckr4 at 3p22 (Ref. 32). No chromosomal localization for the ccckr3 gene has yet been reported. Interestingly, a number of genes encoding chemokine-receptor-like orphan receptors are also located in the region 3p21–22, including chemokine β receptor-like 1 and G protein-coupled receptor 5. The gene for DARC resides on chromosome 1q22–23 (Ref. 33).

Signalling pathways

Receptor activation by chemokines is generally sensitive to pertussis toxin, although a pathway insensitive to this toxin also exists for IL-8 that involves activation of G α 14 and G α 16 (Ref. 34). Activation of heterotrimeric G protein complexes results in dissociation of the α subunit from the $\beta\gamma$ subunits and leads to activation of phospholipase C (PLC) β 1 and β 2. PLC activation results in the hydrolysis of phosphatidylinositol 4,5-bis-

phosphate to produce the second messengers inositol (1,4,5)-trisphosphate (IP₃) and diacylglycerol (DAG). These second messengers trigger a signalling cascade in which a variety of effectors are phosphorylated and activated, ultimately giving rise to diverse cellular responses such as chemotaxis, degranulation and respiratory burst. It appears that G α 2 is distinct in this respect since, although it couples to G α i, stimulation of the receptor with MCP-1 does not result in IP₃ production¹¹. There is now evidence to suggest that multiple and distinct signalling pathways exist for chemokine receptors, depending on the cell type, receptor and ligand involved^{35,36}. Recombinant chemokine receptors stably expressed in appropriate cell lines should prove to be useful tools for dissecting the operative pathways.

Chemokine receptors in disease

The presence of chemokines in a number of human disease pathologies with associated inflammation has been widely demonstrated (reviewed in Ref. 37). The use of specific anti-chemokine antibodies has been shown to curtail inflammation in a number of animal models (e.g. anti-MIP-1 α in bleomycin-induced pulmonary fibrosis³⁸ and anti-IL-8 in reperfusion injury³⁹). 'Knockout' mice for the gene encoding MIP-1 α have no overt haematopoietic abnormalities but are resistant to myocarditis induced by Coxsackie virus and show reduced pneumonitis following infection with influenza virus, suggesting that MIP-1 α is an important mediator of virus-induced inflammation⁴⁰.

Perhaps the clearest link of any chemokine receptor with disease is the relationship between DARC and malaria. DARC functions not only as a promiscuous chemokine receptor but also as a receptor for the malarial parasite *Plasmodium vivax*. DARC is absent on the erythrocytes of individuals in certain ethnic groups who are resistant to infection by *P. vivax*²⁰. Yet it appears to be expressed normally elsewhere in these individuals. The repression of the gene expression

in erythrocytes is due to a point mutation in the erythroid promoter⁴¹.

The identification of murine homologues of chemokine receptors (based on sequence, tissue and cellular distribution, and functional similarities) will facilitate the construction of knockout mice that should then give insight into the biological relevance of chemokine receptors in disease. The murine IL8_B homologue is the only receptor so far for which such published data exist: mice lacking this receptor show significantly reduced neutrophil migration to inflammatory sites compared with normal mice⁴².

Closing remarks

Evidence is accumulating to indicate that chemokines and their receptors play a pivotal role in inflammation. Multiple chemokine receptors with considerable overlapping ligand specificities have now been identified and leukocytes generally express several different receptor types. The basis of this redundancy is unclear. *In vivo*, it is likely that both chemokine and specific chemokine receptor expression is regulated temporally and spatially. It also appears that different ligands may activate distinct signalling pathways at the same receptor. This suggests that specific receptors are likely to play a key role in a given disease state. Thus, the development of inhibitors targeted to distinct receptors will be important in the therapeutic intervention of inflammatory and viral diseases.

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Is there a 'lock' for all agonist 'keys' in 7TM receptors?

Thue W. Schwartz and Mette M. Rosenkilde

It is generally assumed that the superfamily of rhodopsin-like seven transmembrane domain (7TM) receptors must have a common molecular activation mechanism. This is based on the structural homology of the receptors, and the fact that they act through a common set of G proteins. The ligands for 7TM receptors cover all classes of chemical messengers: from metal ions and monoamines, purines and lipids to peptides and large proteins. Despite this great diversity in size and chemical composition, it has been assumed that these ligands still activate their respective receptors using a common mechanism. The initially characterized monoamine-binding site was the most obvious candidate for a general active site or a common 'lock' for all agonist 'keys'. Recent studies, for example on bradykinin and thrombin receptors, indicate that this may not be so, and

evidence has begun to accumulate in favour of a receptor model with no requirement for a common active site.

The 'lock' for monoamine 'keys' is located deep within the main ligand-binding crevice

The binding site for catecholamines on adrenoceptors was characterized both by mutational mapping and by fluorescence spectroscopy in a pioneering series of papers^{1,2}. The most crucial contact points are believed to be an Asp on TM-III (AspIII:08), two Ser residues on TM-V (SerV:09 and SerV:12), and a Phe on TM-VI (PheVI:17) - all located deep within the main ligand-binding crevice (see Figs 1 and 2). Most convincingly, the specific interaction between the amine function of the ligand and AspIII:08 on the receptor was shown by mutually complementary modifications on both the

ligand and the receptor³. As presumed contact points for other monoamine ligands were subsequently identified in corresponding or neighbouring positions in their respective receptors, it was suggested that this deeply located pocket serves as a general interaction site, not only for monoamines, but for all agonists of the rhodopsin-like 7TM receptor family^{4,5}. In the molecular models, ligands could reach down and touch this trigger area and thereby activate their respective receptors (e.g. for neuropeptides and glycoprotein hormones)^{6,7}. Only through binding to this common lock would agonists be able to start a cascade of conformational alterations down through the TMs, which eventually would transfer the signal to the G protein⁸.

However, results from mutational mapping experiments indicate that certain peptides such as substance P might in fact not contact the deeply located monoamine binding residues^{9,10}. It was suggested that such peptides could, instead, activate their receptors merely by stabilizing an active conformation through ligand-

T. W. Schwartz,
Professor,
and
M. M. Rosenkilde,
Medical Student,
Laboratory for
Molecular
Pharmacology,
Rigshospitalet 6321,
Blegdamsvej 9,
DK-2100 Copenhagen
Denmark.